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Enclosure (8)

A PHYSICALLY REPRESENTATIVE AIRCRAFT LANDING GEAR MODEL FOR REAL-TIME SIMULATION

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Abstract

A detailed aircraft landing gear model developed by the authors is presented. The advantages of this model are numerous. Its accuracy is sufficient for engineering analysis, yet it is applicable to real-time applications. The model is able to represent the complex ground reaction behavior required by such conditions as damaged runways, moving landing surfaces, high surface winds, and large asymmetric loads. The various subsystems are modeled in an intuitive manner, facilitating identification and modification of any physical property by the user.

Problems encountered in the course of developing the model are discussed and solutions to these problems are identified. The model has been incorporated into several simulator systems including a high-fidelity F/A-18A-D simulation, and its observed efficacy in this installation is examined. Future plans for enhancement and expansion of the landing gear model are also discussed.

Introduction

To enable the operation of flight simulators for takeoff and landing maneuvers as well as typical ground operations, it is necessary to model the landing gear system. Historically, aircraft landing gear modeling has been necessarily limited to the specific task for which the simulator is destined. Piloted simulators used for flight training generally lack the sophistication required of a landing gear model which is needed for ground-handling studies. On the other hand, detailed landing gear dynamic models that are used to analyze ground handling and acceptability of the landing gear system are typically too complex for use in piloted simulators when only a small fraction of time is spent on the ground during operation.

The advent of more powerful, less expensive computing systems has enabled more and more complex models to be run in real time, encouraging a convergence between engineering and training simulators. A good example of this trend is the development of the Controls Analysis and Simulation Test Loop Environment (CASTLE) by the Manned Flight Simulator facility at the Naval Air Warfare Center, Aircraft Division.[1] Use of the CASTLE shell facilitates the use of complex, high fidelity simulation models in real time with a pilot in the loop. The same models are also employed to perform various off-line engineering analyses.

Notwithstanding this trend, the majority of real-time simulations in use today still include landing gear models of limited suitability for investigating such problems as landing and takeoff with asymmetric loads or non-conventional surface operations. Simulations such as those used at the Manned Flight Simulator are often called upon to provide just such types of analysis with a pilot in the loop as well as in off-line sessions. These simulations require an aircraft landing gear model which accurately represents landing gear behavior in real time while resorting to the use of as few approximations as possible in order to ensure suitability for meaningful analysis. The landing gear model developed by the authors was designed to meet this requirement.

Specification

A landing gear model intended for use in analytical work must meet certain minimum criteria. The model is required to behave appropriately for all typical ground reaction maneuvers experienced on airfields as well as those required for shipboard operation. Typical ground handling simulation requires modeling for taxiing at both very low and very high speeds and for takeoff and landing operations. The model should be able to simulate steering operation on the ground, braking from "rotors tight" all the way to the anti-skid torque level, and sliding both in the forward and lateral directions. Shipboard operation requires the addition of pitch, roll, heave, and yaw motion to the landing surface and possibly the use of a launch bar and a tailhook, depending on the aircraft.

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The model must have adequate fidelity to represent the landing gear of fixed wing aircraft accurately at high descent rates in order to model landings aboard aircraft carriers correctly. For a helicopter or tilt-rotor aircraft, the model should be able to predict the landing gear system response accurately during very slow vertical descent to landing.

In addition, the ability to represent complex ground reaction behavior such as damaged runways, large asymmetric loads, or high surface winds is desired. The model must be robust enough to avoid anomalous behavior in such extreme conditions, and must provide response that is as accurate as possible within the limits of digital simulation.

A particularly desirable trait for a landing gear model is that it be physically representative. The majority of existing real-time landing gear models use simplified or equivalent models of the landing gear system. In these cases, the impact of any parameter adjustment is not always clear, and often results in undesirable side effects. Ideally, all parameters used to define the behavior of parts of the model should be physically meaningful quantities whose impact on the model is easily understood. For example, adjusting the tire pressure should impact the tire force versus deflection property in a predictable way. Further, a physically representative model is required for parametric analysis of a system.

To avoid "reinventing the wheel," it is of great advantage to design the model from the standpoint of reusability. All subsystems should have well-defined inputs and outputs, so a replacement subsystem can be dropped in if the landing gear model is to be installed on a different aircraft simulation, and the standard subsystem model is unable to represent the new aircraft's components in a satisfactory manner. All standard subsystem models should have parameters that are easily understood for use in tuning the model.

Finally, since the landing gear model will find application in real-time simulation, it is important that the model be as efficient as possible. This stipulation precludes running the entire simulation at hundreds or thousands of cycles per second to obtain reasonable model behavior, and requires that frequency-independent guarantees of stability be included in the model.

Potential Pitfalls

An aircraft landing gear assembly represents a complex system that contains much faster dynamics than the aircraft as a whole in each of its several axes of motion. Some higher frequency dynamics associated with the landing gear system do not impact the overall operation of the simulation and are usually not observable by the pilot or onboard instrumentation. On the other hand, it is necessary to model some of the physics associated with these fast dynamics in order to have a realistic model throughout the operational range of the landing gear. Some of these issues are addressed below.

Discrete Time

The first major concern is one inherent to digital simulation, the fact that time is discontinuous. Given the typical update rate of high fidelity flight simulation models, this issue can largely be ignored in the creation of other simulation components such as aerodynamics or engine models. The landing gear model however, poses special challenges. Since it is not practical to significantly increase the update rate of the entire simulation, it is necessary to identify the dynamic states of the landing gear and isolate those which contribute significantly to the overall behavior of the simulation. The landing gear model must be designed to allow for proper update of these states on a digital computer.

Boundary Conditions

Another potential problem in the development of a landing gear model is the presence of discretized boundary conditions. In the case of the aircraft landing gear, the exact inertial location of the landing gear relative to the landing surface is required to compute the correct reaction force. In a digital simulation, this relative position is updated at regular intervals. Under certain conditions, the change in the relative location of a wheel and the landing surface in a single iteration of the simulation may cause the physical limits of the landing gear assembly to be exceeded. This does not necessarily imply a crash condition.

For example, during an aircraft carrier landing, a typical high performance fighter aircraft simulation updated at a rate of 60 times per second will compute a closure rate of approximately 8 centimeters per time step. Since the change in wheel position each time the aircraft states are updated is comparable to the maximum nose gear tire deflection, this discrete position change can lead to situations in which the simulation detects no tire deflection one frame, and nearly full deflection the next. Such a deflection produces a position-based, spring-like force which, because of the discontinuity in wheel position, will itself be discontinuous. The reaction force can be unrealistically large, bouncing the aircraft back into the air.

Predictability and Stability

The behavior of the landing gear model must be predictable and stable. If these characteristics are absent, simulation users will understandably express doubts in the accuracy of the model.

A model possesses predictability if it reacts in the same way every time it encounters the same set of circumstances, from the pilot's point of view. In other words, relatively small deviations in any part of the model's environment must not result in relatively large deviations in the behavior of the model.

To be considered stable, a model must be free of noticeable drift when stopped in any axis. Any simulation running on a digital computer must take into account the numerical precision available on the given platform. Equations must be coded in such a way that the loss of precision that occurs with each mathematical operation is not propagated over many frames. If the loss of precision is allowed to compound, the model may experience drift when it should be standing still, or may track an incorrect ground path.

This concern is unique to landing gear modeling, as minor errors in aircraft trajectory caused by other models are not readily detectable by the pilot. By definition, there is always a nearby visual reference when the aircraft is sitting on its landing gear. The proximity of this reference enables the pilot to notice any anomalous excursions easily. Once the vehicle is airborne, minor deviations from the flight path that ought to be followed are not discernible.

Model Development

To satisfy the given requirements while avoiding the indicated pitfalls, the authors have developed a new landing gear model based on existing models[2,3,4] and on descriptions of landing gear components in the literature. The development of this model was based on many years of simulation and landing gear analysis performed at the Manned Flight Simulator and other government and industry facilities. The model is an extension and refinement of existing models, and represents an attempt to simulate the dynamics of the landing gear more accurately while maintaining usability in real-time simulation. In addition, the structure of the model has been kept as generic as possible, with data and interface requirements for installation under new aircraft simulations explicitly specified.

Physically, each assembly consists of numerous dynamic systems, including the tire, the wheel, and one or more struts. In the development of several previous landing gear models, computational requirements and other restrictions on the level of model complexity made it necessary to combine the longitudinal tire dynamics with equivalent strut dynamics. This sort of modeling approach chooses to ignore the higher frequency dynamics of the tire and to replace the overall system dynamics with an equivalent model of the tire-strut combination. Such approximations necessarily discard some information about the properties of the various landing gear components.

The approach taken for the present work is to model each dynamic system within the landing gear assembly separately and to bring these elements together to form a cohesive model, in order to provide a model that remains as physically realistic as possible. Nevertheless, some approximations and simplifications must still be made in order to address the potential pitfalls.

The primary obstacle to avoiding oscillatory behavior when the aircraft is stopped in any axis is the reactive nature of pneumatic tires. To address this problem, a reaction force prediction scheme is used to determine the static friction force produced by the tires. The forces being produced by all other systems in the aircraft are intercepted before they are sent to the equations of motion and counteracted with an appropriate force from the tires. In this manner, the time lag between the application of an external force and the appearance of the reaction force is circumvented. In addition, distribution of the applied external forces and moments among the active landing gear assemblies is required. This distribution is performed by the wheel model based on the position and loading of each axle.

Various methods have been employed in the past to address the boundary condition problem. Earlier landing gear models have used artificially long struts or tires of exaggerated diameter, causing the aircraft to begin feeling the effects of the ground even while dozens of feet in the air.[5]

In the present landing gear model, the strut and tire dynamics are updated at a high rate relative to the update rate of the simulation,[6] as depicted in Figure 1. Each frame, the aircraft as a whole moves to a new position. For each slow frame executed for the rest of the simulation, the internal fast loop of the landing gear model runs for several fast frames, allowing the strut and tire dynamics to reach a pseudo-equilibrium. The forces produced by the tire once this state is reached are then applied directly to the airframe. Thus, the strut acts on the tire (via the axle), and the tire acts on the aircraft itself. A typical installation has the landing gear model called at 60 Hz by the simulation executive, and the inner fast loop running at a rate of 480 Hz. This fast inner loop allows the strut-tire dynamics to be resolved completely between updates of the aircraft's position,

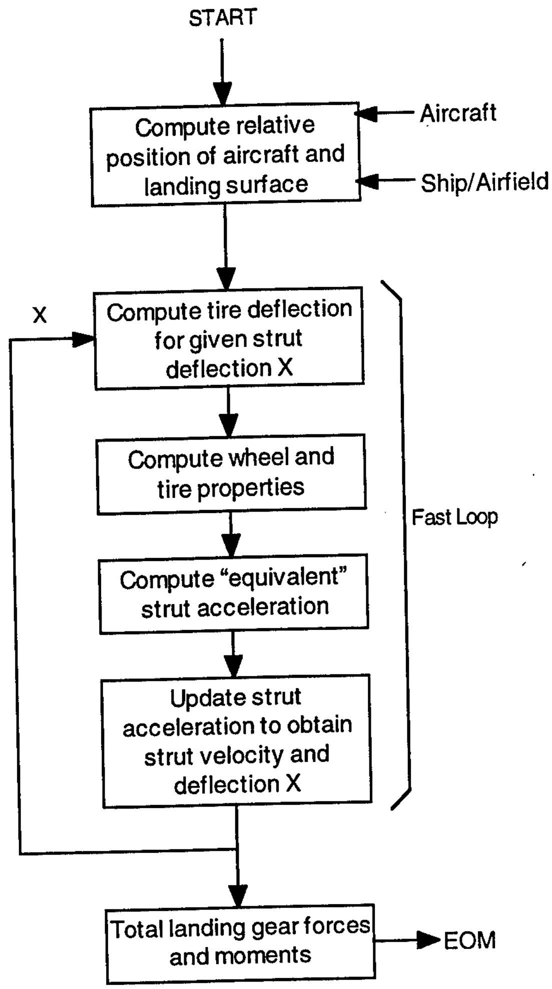

Figure 1. Landing gear model fast loop operation.

avoiding numerical anomalies associated with the boundary condition. This solution was deemed adequate since the mass of the aircraft is several orders of magnitude larger than that of the landing gear assembly.

The equations used in the landing gear model are carefully coded so that any loss of precision caused by round-off error is not propagated over many frames. Fail-safe mechanisms are also built into the code to reject anomalous behavior before it manifests itself just in case the model is placed in an unusual situation, or the operator attempts to run the simulation at an update rate that is too low for accurate function of the landing gear model. In this manner predictability and stability of the model are assured.

Implementation

The landing gear model can be divided into various components or objects which together represent the overall functionality of the desired landing gear. Figure 2 shows the objects selected to represent the

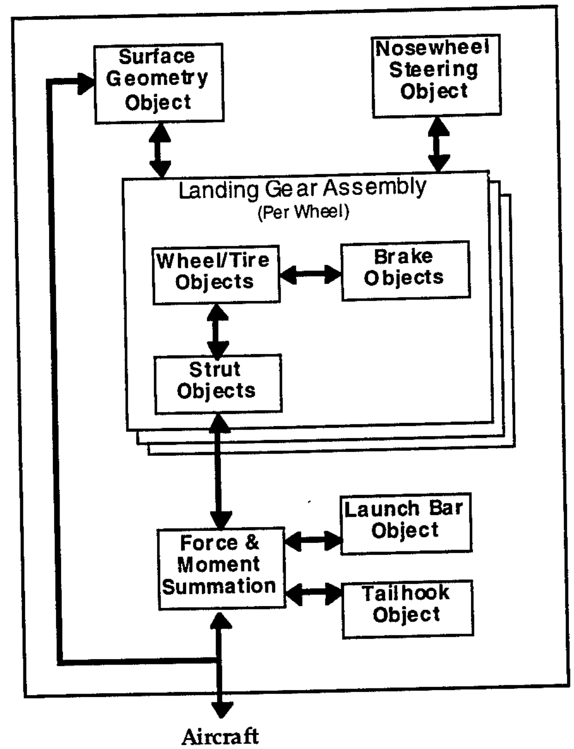

Figure 2. Landing gear model objects.

aircraft landing gear. The model includes runway objects which contain information about the relative position and geometry of the landing surface, a set of wheel and strut objects for each modeled landing gear assembly, a nosewheel steering object, and tailhook and launch bar objects, if required, which act as external forces to the aircraft system. Each landing gear assembly object set is further subdivided into wheel and tire objects, brake objects, and strut objects.

Each object comprises the functions and data used by the corresponding landing gear or simulation component. Dividing the landing gear model into well defined, physically representative objects provides several benefits. The function and interconnection of the various landing gear components are made more understandable by this organization. In addition, when the landing gear model is installed in a new aircraft simulation, any of the objects can be replaced as necessary without requiring a complete revision of the source code. Since the data paths between the objects are documented, it is easy to "plug in" a new object in place of an old one.

Wheel and Tire Objects

The tire model is based on empirical equations from the literature.[7,8] Forces produced by the interaction between the tire and the landing surface are calculated normal to the surface and parallel to it.

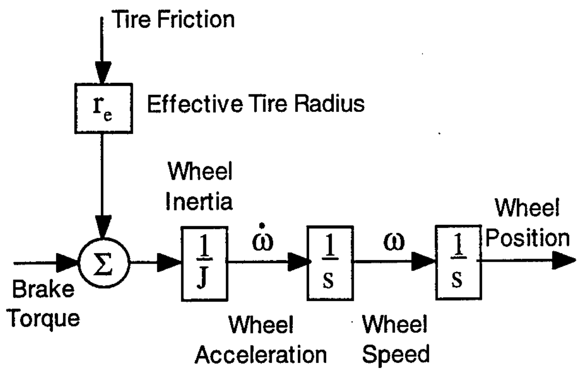

Figure 3. Wheel rotational dynamics.

Although the wheel angular velocity is not directly observable by the pilot, it is needed to properly model the longitudinal motion of the wheel and braking action. In addition, spin-up of the wheel is important in modeling touchdown dynamics.

The rolling torque experienced by a braked wheel is dependent on the slip ratio, defined as:

$$\sigma = \frac{\omega_0 - \omega}{\omega_0}$$

where ω_0 is the angular velocity of the wheel for unbraked rolling, and ω is the wheel angular velocity for braked rolling.[7] When the wheel is rolling at a speed equal to the unbraked nominal speed, the slip ratio is zero and there is no associated rolling torque on the wheel. As the wheel angular velocity is changed, the magnitude of the slip ratio and the corresponding wheel torque magnitude are increased. A slip ratio of magnitude one denotes the point where the wheels are locked. The torques applied to the tire by the ground and the brakes are used to determine the angular acceleration of the wheel each frame, as depicted in Figure 3.

At very low speeds, the slip ratio becomes difficult to calculate due to the digital nature of the system. Therefore, a low speed approximation must be used. This approximation finds slip ratio as a direct function of brake torque, on the assumption that large brake torque will produce a slip ratio of high magnitude, and small brake torque will produce a small slip ratio.

The normalized friction coefficient of the tire is found as a function of the slip ratio. This coefficient is multiplied by the friction characteristic of the landing surface and the tire normal force to obtain the longitudinal force produced at the tire-surface interface.

The wheel model also predicts the side force required to hold the aircraft in a stopped position in order to reject oscillations in the lateral and longitudinal directions. The various wheel objects are required to cooperate to determine how external forces and moments acting on the landing gear model should be divided among the various tires. For example, when faced with a lateral force of 500 pounds due to a crosswind, the wheel objects must decide how much of this force must be opposed by each wheel. This problem is not a simple one, and at the moment has only been coded for the case of tricycle landing gear.

Brake Objects

The baseline landing gear model contains a very simple brake model with a rudimentary anti-skid braking system. Brake pedal inputs from the pilot are converted to a corresponding brake pressure, and an appropriate torque is applied to the axle. The anti-skid braking algorithm monitors slip ratio and limits brake pressure as required to avoid skidding. Various parts of this model may be replaced with more complex objects for braking system analysis tasks. For example, the simplified anti-skid system may be replaced with models for wheel speed sensors, brake pressure sensors, and the actual anti-skid braking algorithm for the aircraft being analyzed.

Strut Objects

A strut object contains only one degree of freedom, the strut deflection. The deflection of the strut is used to determine the location and orientation of the axle, which in the most general sense has four degrees of freedom: three translational and one rotational (that is, tilt or "roll"). The actual number of degrees of freedom that the axle has is dependent on the number of struts contained in the landing gear assembly.

A typical strut assembly such as that found in the main landing gear of the F/A-18C (Figure 4) contains a single strut and one or more rigid members. The deflection of the single strut is translated in real-time into the location and tilt of the axle through the use of

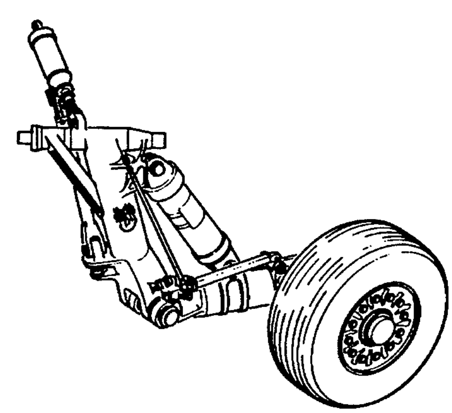

Figure 4. F/A-18C main landing gear assembly.

pre-computed lookup tables. A linear function interpolation is used in obtaining these values for the sake of efficiency. In principle, any number of struts and rigid members can be modeled in each landing gear assembly, as appropriate.

Steering Objects

The steering model introduces another degree of freedom to the axle by allowing yawing motion. This object is generally used to represent steering of the nosewheel in aircraft with conventional landing gear. The basic model includes a simple actuator model for pilot-commanded steering as well as nosewheel castoring.[9]

Surface Geometry Objects

The landing surface model in the simplest sense represents a flat plate on which the aircraft can land. To this simple concept are added several enhancements, the most important of which is the ability to allow the plate to move in real-time. This motion capability is necessary to provide simulation of shipboard operations, with an aircraft carrier deck possibly pitching in heavy seas. In addition, refinements such as differing surface orientations and compositions, damaged surfaces, and structures are possible, features which are important for analysis of aircraft-surface interaction.[10]

Launch Bar and Tailhook Objects

The landing gear model contains provisions for fixed-wing aircraft operations from an aircraft carrier in the form of a launch bar object and a tailhook object. These objects are meant to interact with an external ship model containing catapults and arresting gear.

Force and Moment Summation

An executive routine is provided with the landing gear model. It is the responsibility of this routine to ensure that all the landing gear objects are invoked properly and at the correct update rate. The executive transfers the forces and moments generated by the various objects to the proper coordinate frame and reference locations and sums them. The resulting total ground reaction forces and moments are passed to the aircraft equations of motion module.

Installation and Evaluation

The landing gear model was first installed in a high-fidelity simulation of an F/A-18C aircraft used in a pilot-in-the-loop simulator. Pilots experienced in flying the actual aircraft were asked to perform various operations in the simulator involving the landing gear. Takeoffs and landings from airfields as well as moving aircraft carriers were performed, both with and without crosswinds. Simple taxi tasks such as minimum radius turns and navigation from the ramp to the active runway were also carried out. The pilots' comments about the handling qualities of the aircraft were noted and used to evaluate the landing gear model. On the whole, pilots have been pleased with the response of the model, describing it as more representative of the behavior of the actual aircraft than the previously employed simplified real-time model.

Successful installations have also been performed in other high-fidelity simulations, from large fixed-wing cargo aircraft to tilt-rotor aircraft. The model has received favorable pilot comments during evaluation of these installations as well. However, no rigorous validation of the model has been performed for any aircraft. This omission is due to the lack of available detailed flight test data for aircraft operating on or near a landing surface.

Future Work

The landing gear model presented here was designed to allow for incremental or program-specific improvements to the baseline code. Work is ongoing to improve the accuracy of the landing gear model by evaluating the effects of the empirical equations used in the tire and strut models and determining any possible deficiencies. Other specific enhancements and improvements planned for the landing gear model include better distribution of reaction force between various wheel objects and more detailed surface modeling.

Validation against actual aircraft data is an important goal. The quest to obtain accurate and complete data for use in validating the model has yet to yield results. The ideal solution would be to instrument an aircraft specifically for landing gear model validation and to specify the data set and maneuvers required.

Conclusion

Landing gear models intended for use in real-time simulation are not as detailed as those employed solely in off-line engineering analysis. The model outlined here represents an attempt to merge the two types of simulation models to obtain the best of both worlds. This model shows promise for use in the next generation of real-time flight simulators in support of flight test efforts, pilot familiarization, envelope expansion, and accident investigation. Once a rigorous validation effort has been completed, confidence in the accuracy of the model will be confirmed.

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